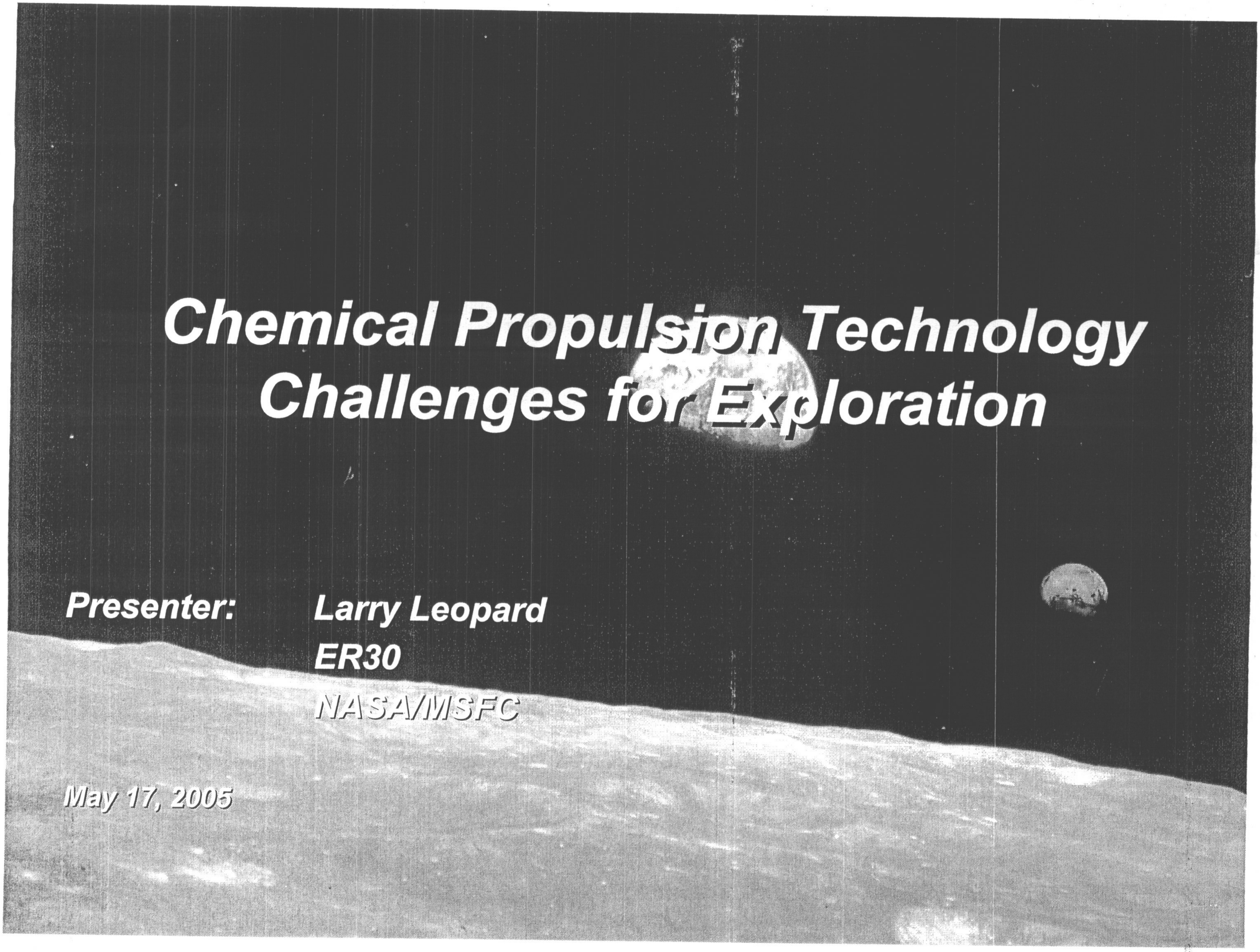
Chemical Propulsion Technology
Challenges for Exploration
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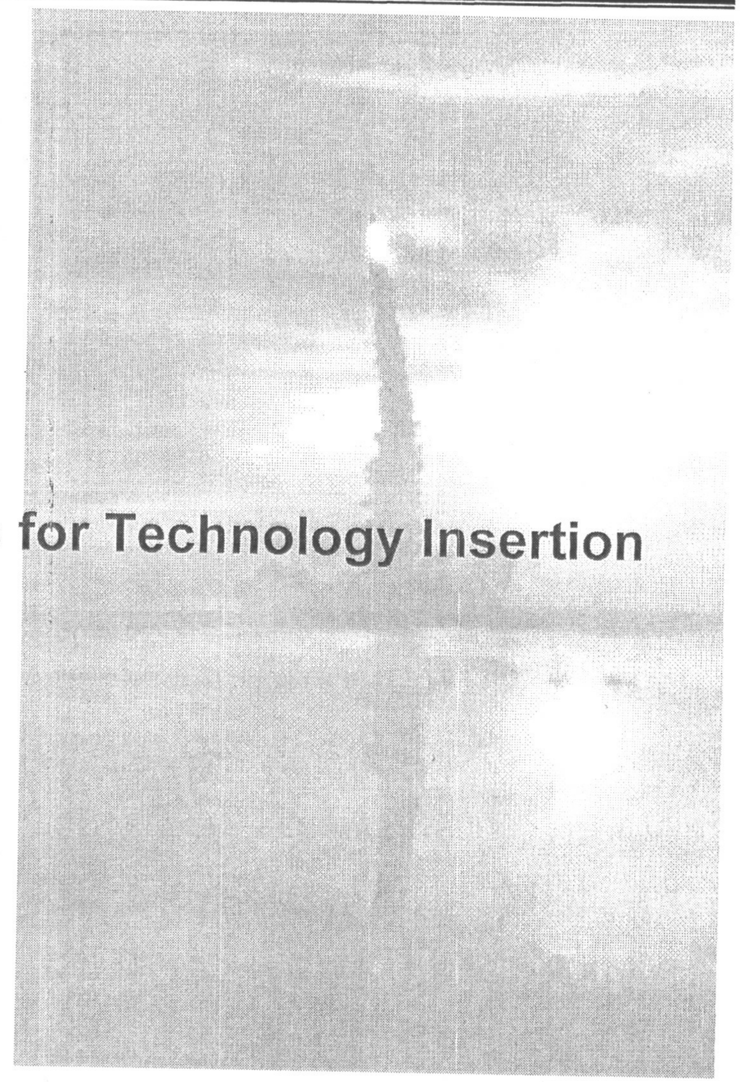
ER30
NASA/MSFC
May 17, 2005

Agenda

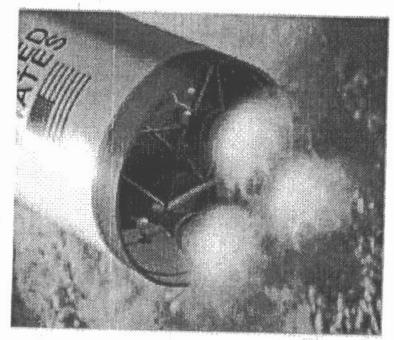
- Introduction
- Assumptions & Scope
- Reference Mission (Notional)
- Propulsion Elements & Opportunities for Technology Insertion
- Issues
- Summary & Conclusions

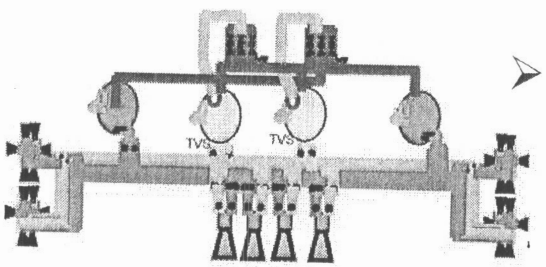


Introduction

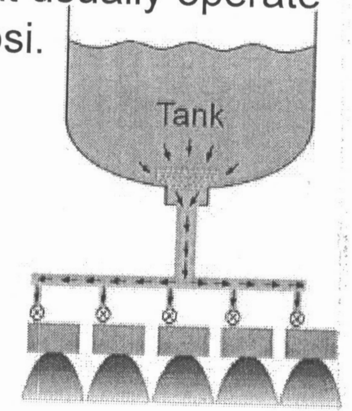
- Chemical propulsion covers all propulsion subsystems that involve the chemical reaction of propellants to move or control the space craft

- Specific elements include
  - Main Engines
    - Provides main propulsive forces for Earth to Orbit, Orbit Trans Planetary Trajectories and extra planetary landing / ascent





  - Reaction Control Systems / Orbital Maneuvering Systems
    - Orbit maintenance, position control, station keeping and spacecraft attitude control
    - Pressure-fed RCS propulsion systems, that usually operate somewhere in the range from 200 to 400 psi.
  - Main Propulsion Systems (MPS)
    - MPS is defined as the vehicle fluid systems that support main engine operation
    - It is a means of integration between the engine, vehicle systems and propellant tanks

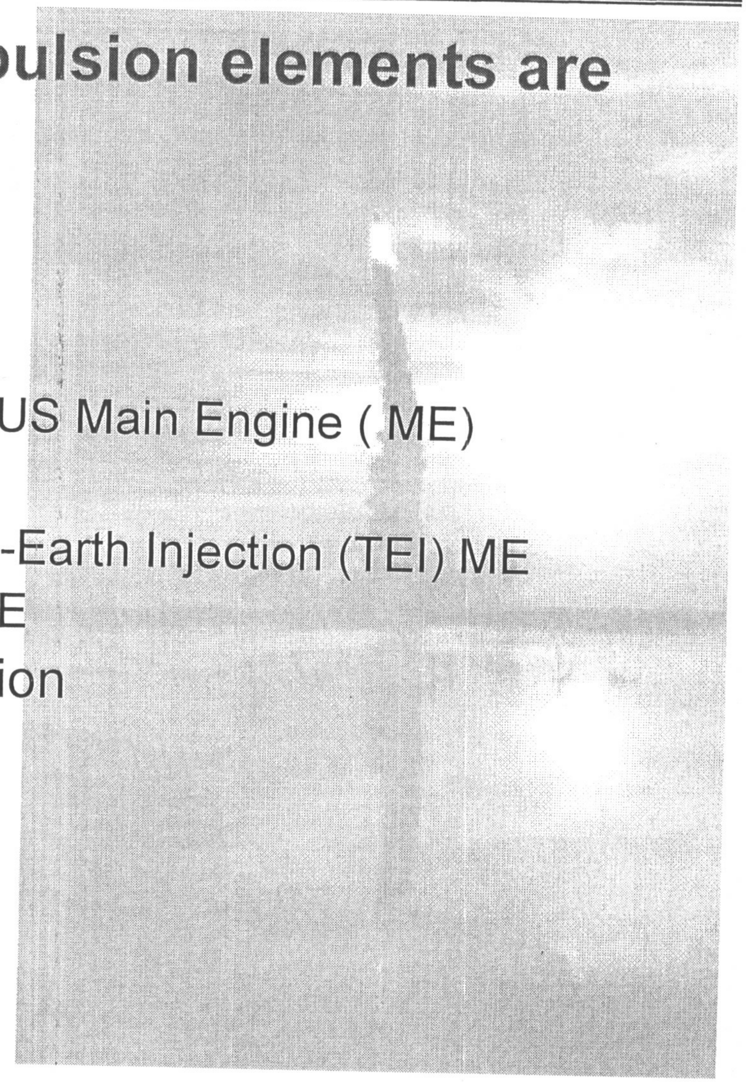


Assumptions

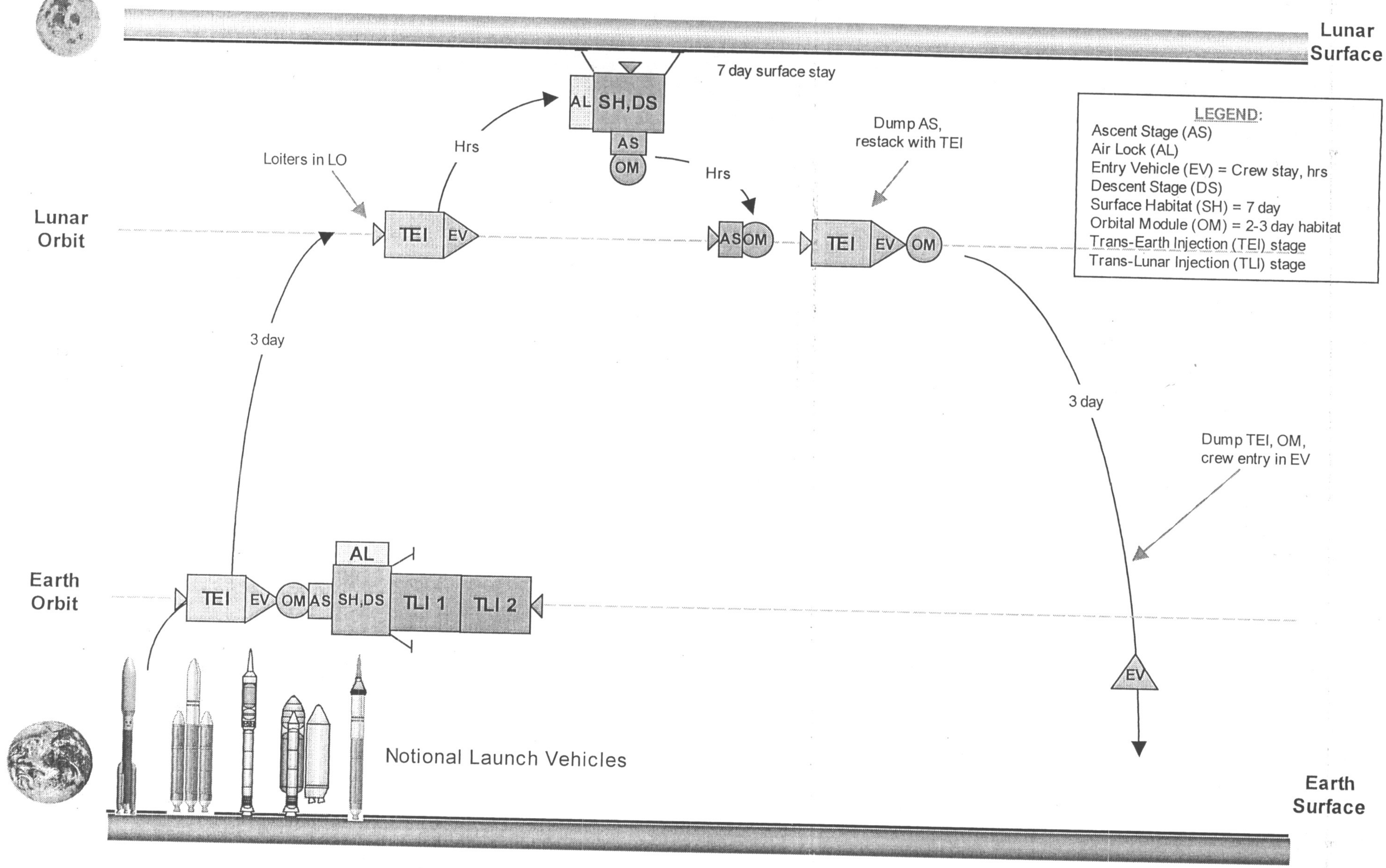
- Solution trade space still open
- Propulsion requirements derived from vehicle and mission requirements
- Commonality in design and technology-base favored where practical
- Technology is broadly defined and includes enhanced design, development, and testing activities, reconstitution of technical skills and capabilities and development of new, more efficient tools and methods.
- Mission to the lunar surface is the focus of this propulsion technology briefing. Mars mission impacts noted for some key technologies.

Scope

- **For discussion purposes, propulsion elements are grouped as follows:**
  - Boost Main Propulsion
  - Boost-Assist Propulsion
  - Upper Stage (US) Main Propulsion
    - Crew and Cargo Launch Vehicle (LV) US Main Engine (ME)
  - In-Space Transfer Propulsion
    - Crew Exploration Vehicle (CEV) Trans-Earth Injection (TEI) ME
    - Lunar Earth Departure Stage (EDS) ME
  - Lander / Ascent (L/A) Stage Propulsion
  - Crew Safety for Ascent
  - Reaction Control System (RCS)
  - Main Propulsion System (MPS)



Notional Lunar Reference



LEGEND:

Ascent Stage (AS)
Air Lock (AL)
Entry Vehicle (EV) = Crew stay, hrs
Descent Stage (DS)
Surface Habitat (SH) = 7 day
Orbital Module (OM) = 2-3 day habitat
Trans-Earth Injection (TEI) stage
Trans-Lunar Injection (TLI) stage

Apollo Required Significant New Starts - Ambitious Current Missions Require Additional Enabling Technologies

Number of New Rocket Engines Developed for the Apollo Mission

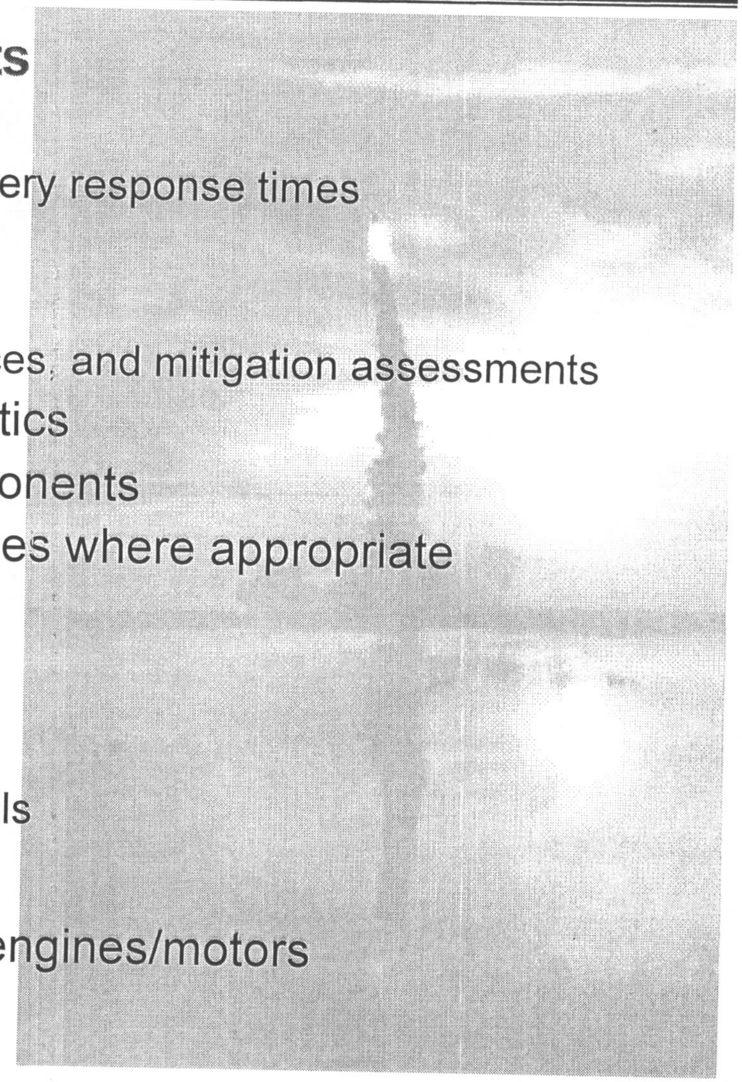
SATURN 5 / F-1 engine	F-1
S-2 second stage S-1VB	J-2
RCS Thruster	R4-B
Solid Escape Tower Rocket	E R
SE-7 ULLAGE Control S-2	SE-7
SE-8 Command Module RCS S-14B	SE-8
TRW ULLAGE Rocket	UC-1
Service Module Main Engine	AJ10-137
LUNAR Descent Engine	LMDE
LUNAR Ascent Engine	LMAE
Total # of new engines developed for Apollo	10

Opportunities Exists to Improve Propulsion's Role In Current Missions

Total Number Of Rocket Engines/Motors Per Flight of Each Apollo Mission

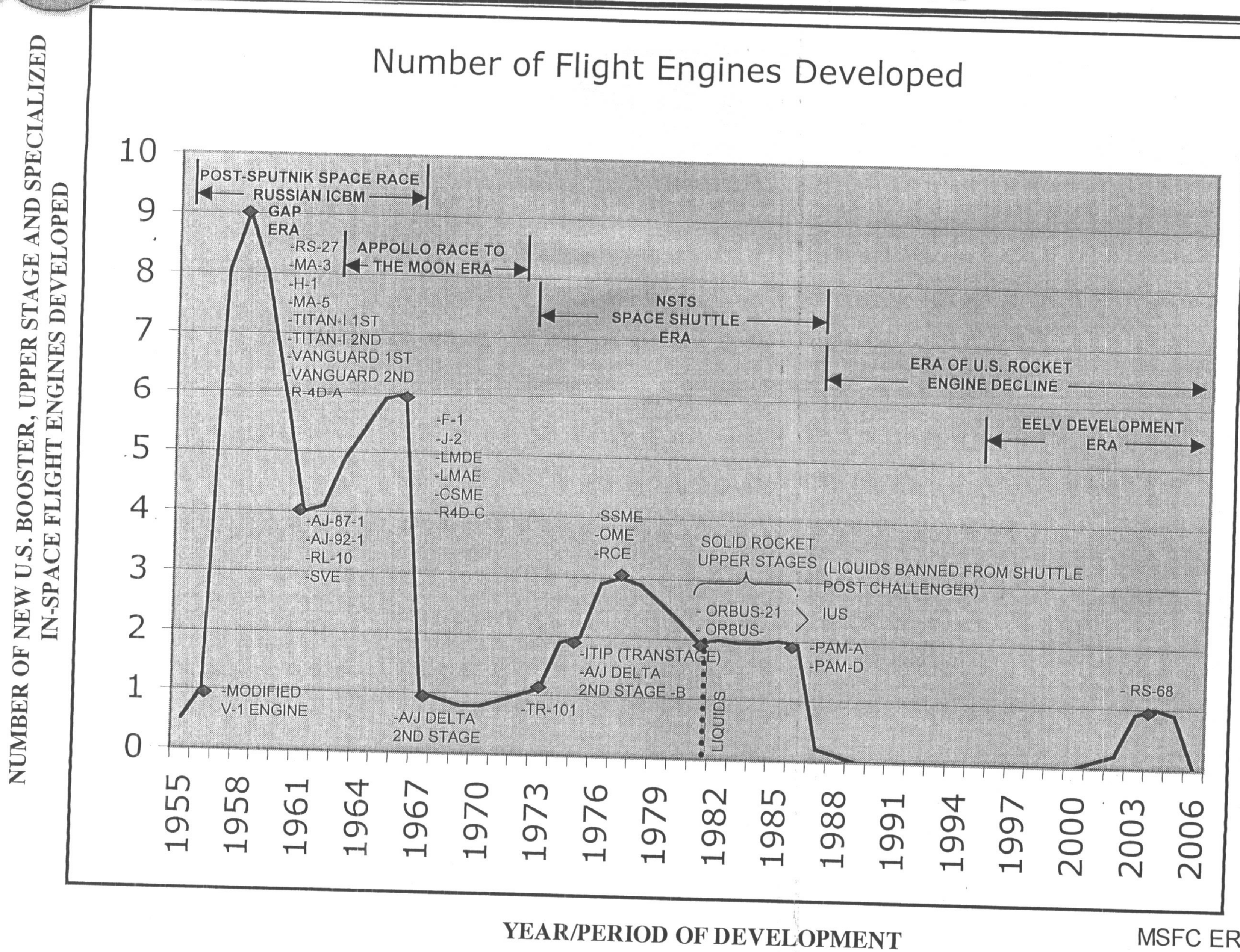
S-IC Stage	F-1 Engines LO_2/RP-1/1.5 MLB_F/ ROCKETDYNE (R/D)	5
	Retrorockets, solid fuel THIOKOL	8
S-II Stage	J-2 engines LO_2/LH_2 / 200KLB_F / R/D	5
	Ullage rockets, S-IC/S-II interstage 100 LB_F/ R/D	4
	Retrorockets for two auxiliary propulsion system modules Solid Rockets - THIOKOL	4
S-IVB Stage	J-2 engine / R/D	1
	Main ullage rockets, jettisonable MARQUARDT	2
	Rockets for two auxiliary propulsion systems modules 100 LB_F/ TRW	8
Command Module	Fwd. compartment reaction control engines (pitch) 100 LB_F MARQUARDT	2
	Aft compartment reaction control engine (pitch) 100 LB_F MARQUARDT	10
	Roll engines 100 LB_F MARQUARDT	2
Service Module	Service Module Engine (SME) N_2O_4/A-50, 20KLB_F AEROJET	1
	RCS engines 100 LB_F MARQUARDT	16
Lunar Module	Decent engine, N_2O_4/A-50 10,000 to 1,000 LB_F Deep-Throttling TRW	1
	Ascent engine, N_2O_4 3KLB_F BELL/ROCKETDYNE	1
	RCS engines 100 LB_F MARQUARDT	16
TOTAL		86

Opportunities for Technology Insertion
General



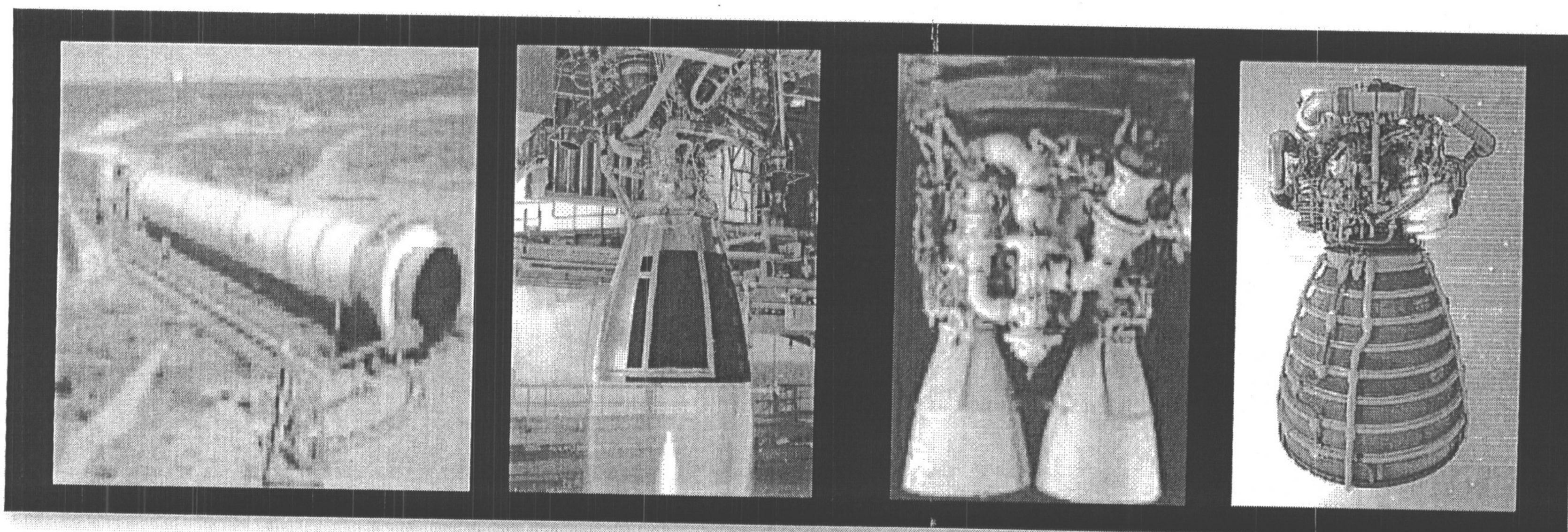
- **Safety and Reliability Improvements**
  - ➢ Safe shutdown and operation
    - Improved fault detection, isolation, recovery response times
    - Failure containment
  - ➢ Accurate risk & life assessments
    - Physics-based probabilities, consequences, and mitigation assessments
  - ➢ Integrate fault diagnostics and prognostics
  - ➢ Improve reliability on highest risk components
  - ➢ Improve fault tolerance and redundancies where appropriate
  - ➢ Improve fault avoidance
- **Performance Enhancements**
  - ➢ Improvements in thrust/weight
    - Replacement of heavier/obsolete materials
- **Cost Reduction**
  - ➢ Improve manufacturing techniques for engines/motors
- **Reconstitute Vendor Capability**

NEW FLIGHT ROCKET ENGINE DEVELOPMENTS BY APPROXIMATE YEAR/PERIOD



Boost Propulsion

- **Background**
  - Existing engines and motors:
    - Evolved Expendable LV's (EELV): Isp: 340 - 420 sec (vac), propellants: liquid oxygen (LOX), liquid hydrogen (LH2) or RP, thrust: 740-940 klbf (vac)
    - Shuttle: Isp: 270 (solid) - 455 sec, propellants: LOX, LH2, or solid, thrust: 470k to 2.6M (solid) lbf
- **Possible Options**
  - Highly reliable, Low Cost EELV Engines
  - Highly reliable, Low Cost Shuttle Systems – Reusable Solid Rocket Motor (RSRM), Space Shuttle Main Engine (SSME)

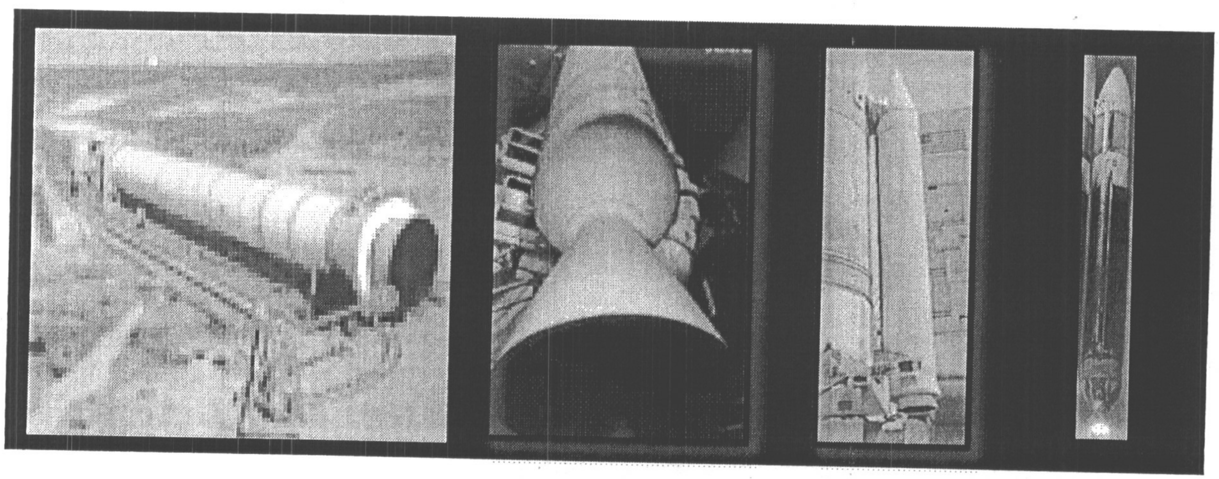


Opportunities for Technology Insertion
Boost Propulsion

- **Safety and Reliability Improvements**
  - Safe shutdown and operation
    - Fix known problems (e.g., leakage, welds, cracks)
    - Reduce criticality one failure modes
    - Failure containment
  - Integrated fault diagnostics and prognostics
  - Improve reliability on highest risk components (e.g., SSME high pressure pumps: e.g., knife edge seals / flowliner, main combustion chamber, nozzle: e.g., option of channel wall nozzle)
  - Accurate risk assessments
    - Enough data to support assessments
      - Service/fatigue life, factors of safety, fracture control, process control, performance & environments, hardware pedigree, as built vs design, cost & maintenance data
- **Performance Enhancements / Enablers**
  - Control system for RSRM
  - Improve thrust, Isp
  - Improvements in thrust/weight
    - Replacement of heavier/obsolete materials with advanced materials, composites
- **Cost Reduction**
  - For STS systems, improve turnaround and lower cost of manufacturing of reusable systems that are to be expendable

Boost-Assist Propulsion

- **Background**
  - STS & EELV solid boosters
    - Isp: 240 - 270 sec, propellants: solid, thrust: 200 - 280 klbf to 2.6 Mlbf (RSRM)
  - EELV liquid booster
    - Isp: 420 sec, propellants: LOX, LH2; thrust: 740 klbf
- **Possible Options**
  - Highly reliable and Low Cost EELV Boost Engines/Motors
  - Highly reliable and Low Cost Shuttle-derived System - RSRM and Advanced Segment RSRM

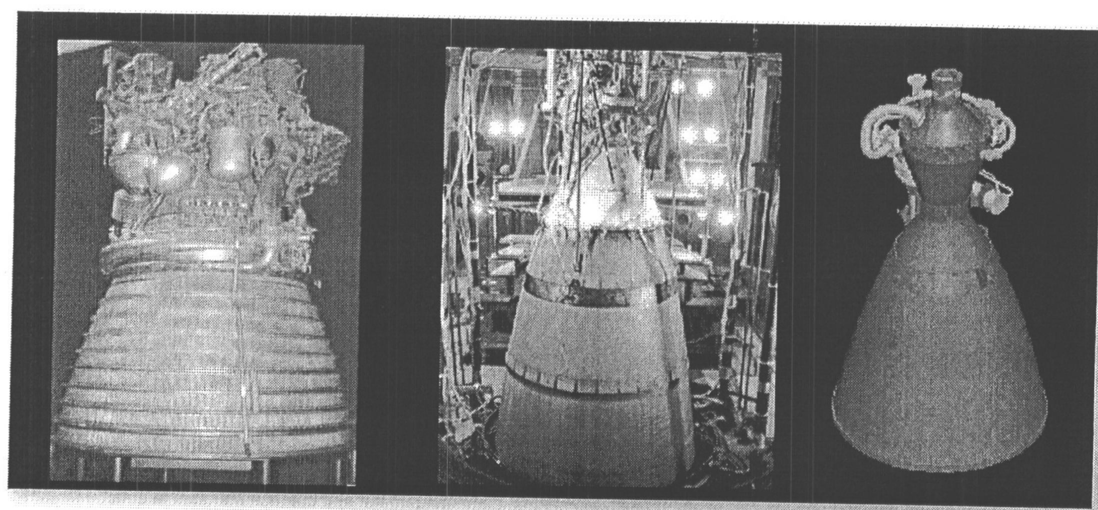


Opportunities for Technology Insertion Boost-Assist

- **Safety and Reliability Improvements**
  - Design improvements
    - Improve design margins; fix known problems such as leakage paths, nozzle cracks and material separations; replace obsolete materials
  - Safe operation and shutdown for liquids, safe operation for solids
    - Reduce criticality one failure modes for all, especially solids
    - Failure containment
  - Improve reliability on highest risk components
  - Accurate risk assessments
    - Enough data to support assessments
      - Service/fatigue life, factors of safety, fracture control, process control, performance & environments, hardware pedigree, as built vs design, cost & maintenance data
- **Performance Enhancements**
  - Improvements in thrust/weight
    - Replacement of heavier/obsolete materials with advanced materials, composites
- **Cost Reduction**
  - For STS systems, improve turnaround and lower cost of manufacturing of reusable systems that are to be expendable

Upper Stage Propulsion

- **Background**
  - EELV LOX/LH2 upper stages
    - Isp: 460 sec, thrust: 22 klbf existing; 60 klbf under development
- **Possible Options**
  - CEV LV US; Cargo Only LV US
    - Need is highly reliable, 22 - 265 klbf thrust level, LOX/LH2 engine(s). Options include:
      - Highly reliable EELV upper stage
      - Restart and complete of Saturn V J-2S
      - New design of 25 / 90 klbf class engine
      - Potentially larger thrust class engine for Moon and Mars missions

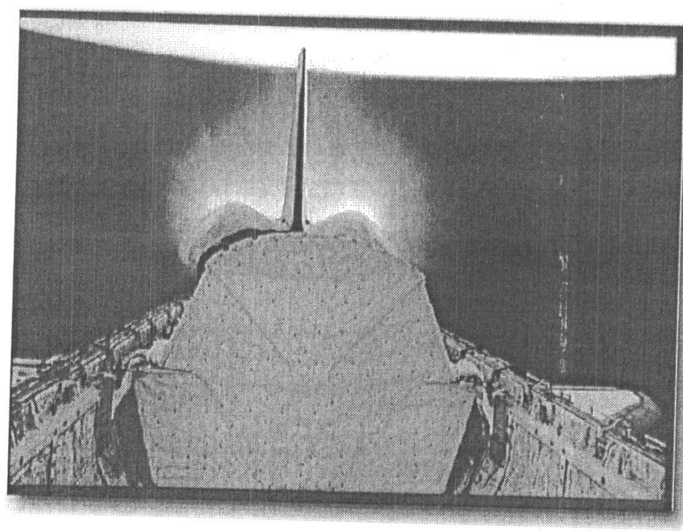


Opportunities for Technology Insertion Upper Stage Engine

- **Safety and Reliability Improvements**
  - Design improvements
    - Improve design margins; fix known problems
  - Safe operation and shutdown
    - Reduce criticality one failure modes
    - Failure containment
  - Improve reliability on highest risk components
  - Robust design and development of new engine/restart
    - Dependent upon option selected; advanced development of highly-reliable turbopumps, injector, igniter, chamber/nozzle and fast-acting valves
    - New design and analysis models and tools (CFD, thermal, environments, performance), advanced material research and fabrication processes
- **Performance Enhancements**
  - Robust to propellant inlet conditions
    - Improve turbopump tolerances; determine impact on combustion stability and performance
  - Multistart / Increased restart capability (>2)
    - Improve turbopump operation, chill-down, and drying
  - Improve thrust, Isp
  - Improve throttling capability
    - Improve valve, injector and turbopump limits
  - Improve packaging

In-Space Transfer Propulsion

- **Background**
  - ➢Current State-of-Art(SOA) is Shuttle Orbital Maneuvering System (OMS) pressure fed hypergolic (NTO/MMH) system, thrust 6 klbf
- **Possible Options**
  - ➢CEV TEI, EDS
    - CEV TEI individual engine need is likely between 5 and 10 klbf thrust
    - EDS individual engine need is likely >25 klbf thrust
      - ❑EDS stage requires higher thrust (pump-fed), higher Isp
    - If In-Situ Return is enabling for Mars then desire may be to gain experience with propellant choice on Lunar missions (LOX/LCH4 or LOX/LH2)



Opportunities for Technology Insertion In-Space

- **Safety and Reliability Improvements**
  - Built-in fault tolerance and redundancy where appropriate
    - Engine out to be traded
  - Robust design and development of new engine
    - Depending upon concept selected, develop small turbopumps with appropriately tight tolerances and performance characteristics appropriate to wide throttle ranges
    - Depending upon concept selected, develop engine appropriate for operation with alternative fuels - turbopumps, injectors, chamber, igniter, ducts and feedlines
- **Performance Enhancements**
  - Support number of restarts (up to 6 CEV TEI, 10+ Mars missions)
  - Support longer duration firings (4000+ sec Mars missions)
  - Improve packaging
  - Achieve commonality (e.g., CEV TEI w/ Lunar Lander; US w/ EDS)

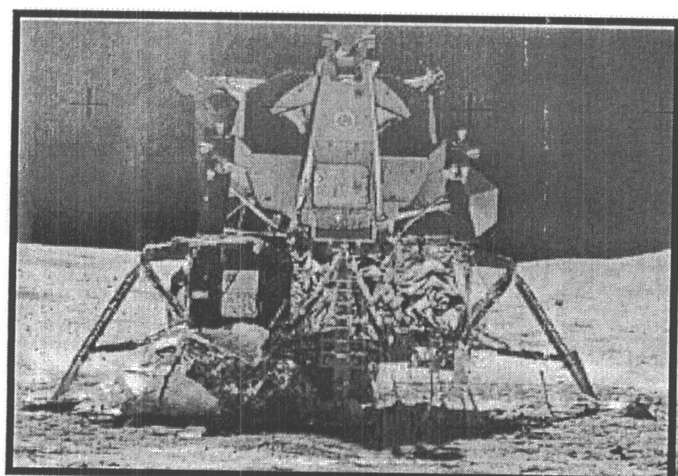
Ascent / Descent (A/D) Propulsion

Background

- Designs still exist for Apollo Lunar Excursion Module Descent and Ascent Engines; 10 and 3.5 klbf thrust; storable NTO/Aerozene 50
  - Hypergols - low and uncertain supply, high cost
  - Commonality a goal (CEV TEI, A/D)

Possible Options

- New or restarted design Lander/Ascent individual engine need is between 5 and 10 klbf thrust. Lunar descent engine needs throttling capability (< 50% RPL).
- If In-Situ Return is enabling for Mars then desire may be to gain experience with propellant choice on Lunar missions (LOX/LCH4 or LOX/LH2)

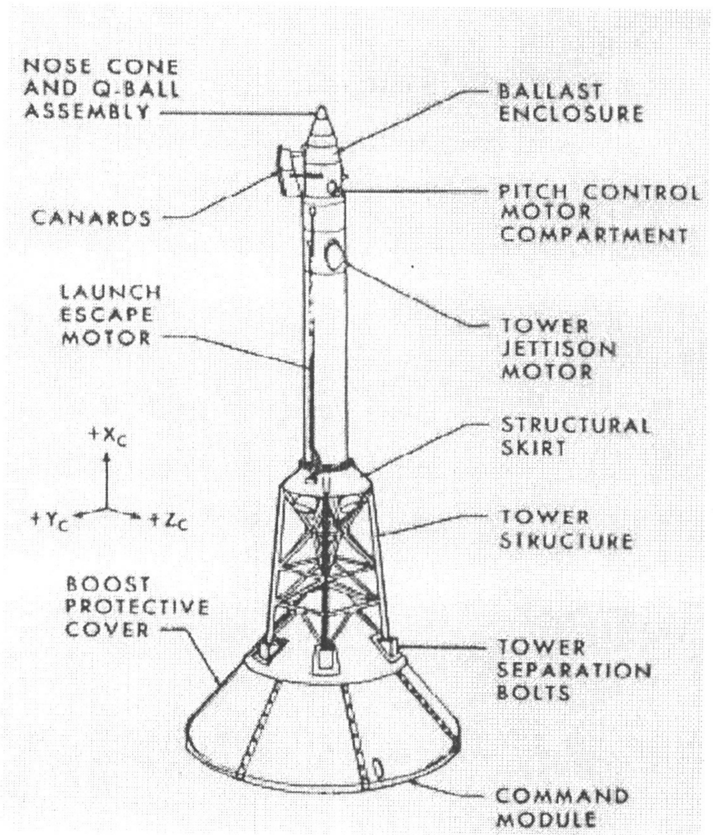


Opportunities for Technology Insertion A/D

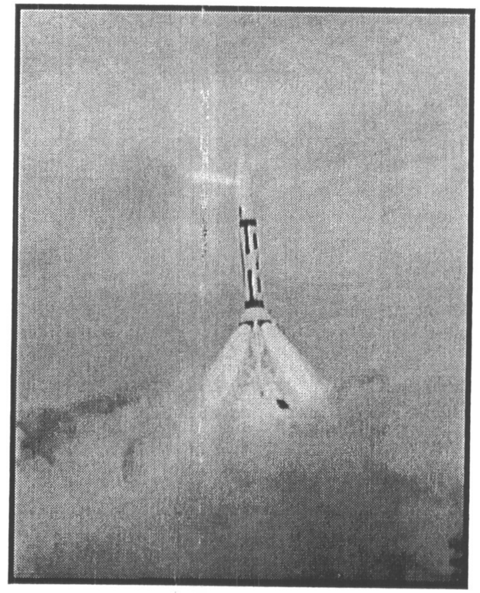
- **Safety and Reliability Improvements**
  - Built-in fault tolerance and redundancy where appropriate
    - Engine out to be traded
  - Robust design and development of new engine/restart
    - Ignition Systems for Cryogenic Engine Options
    - Highly Reliable, Deep Throttle/Low NPSP Cryogenic Turbopumps
    - Deep Throttle Cryogenic Injectors
    - Highly Reliable, Low Leakage Valves/Actuators
    - Long Life, High Durability Thrust Chambers With Advanced Cooling
    - Engine Health Management Prognostics and Diagnostics
    - Improved Turbomachinery and Combustion Device Performance and Reliability Models
- **Performance Enhancements/Enablers**
  - Support deep throttling
  - Improve packaging
  - Achieve commonality (w/ CEV TEI, Mars Ascent Vehicle)

Ascent Crew Safety Propulsion

- **Background**
  - ➢Designs still exist for Apollo Launch Escape System
- **Possible Options**
  - ➢New or restart crew safety design - appropriately sized with improved packaging and active trajectory control.



Apollo Launch Escape System



Pad Abort Demonstration With Escape and Pitch Motor Firing

Opportunities for Technology Insertion
Crew Safety

- **Safety and Reliability Improvements**
  - Robust design and development of crew safety propulsion
- **Performance Enhancements**
  - Packaging - provide for stability and control
  - Reduce weight - composite case
  - Solid propellant gas generator for pitch and jettison motors (active trajectory control system)

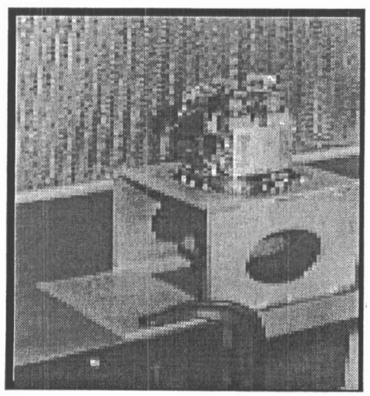
Reaction Control System (RCS)

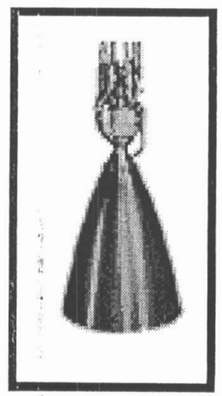
Background

- RCS for LV, US, CEV TEI, EDS, Lander and Ascent Stages
- RCS Need is 100 to 1000 lbf thrusters, Isp 310-340 sec; thrusters exist in desired thrust range
- Current SOA for propellant selection is storable hypergolic propellants
  - However, in general, the desire is for better packaging and performance, lower power draws from heaters, less dependence upon low and uncertain supply of costly hypergols, and a goal of more common systems. Unknown applicability of hypergols to Mars missions.

Possible Options

- Basic performance requirements for notional Lunar mission could be met with current SOA (storable hypergols).
- Trade space is open for other options depending on whether reliability and performance gains are required as concepts mature and whether in-situ precursor demonstrations are required





Opportunities for Technology Insertion
RCS

- **Safety and Reliability Improvements**
  - Improved fault detection, isolation, recovery response times
  - Built-in fault tolerance and redundancy
- **Performance Enhancements / Enablers**
  - Cryogenic reaction control engine (RCE)
    - Cryogenic RCE may be needed for commonality goals and to maximize RCS performance
    - However, no cryogenic RCS systems have flown or engines developed; also, ignition systems unreliable - propellant quality and density variations due to heat leak; temperature varies widely
  - Thermally efficient cryogenic feed systems
    - Low heat-leak feed systems at a low TRL for RCS; efficient methods of chilling in distributed RCS feed systems do not exist
  - Propellant gasification systems
    - Gas RCS systems lower risk and allow liquid storage; may be heavy and complex
  - Common or Combined propulsion/power systems - to save weight but have only been studied
  - Fast-acting, EMA valves for RCS
    - EMA valves should reduce heat leak issues and support efficient throttling; current SOA solenoid valves generate substantial heat
  - RCS systems with other propellant options - CH_4, EtOH, Hypergols

MPS

- **Background**
  - EELV's & Shuttle
  - MPS Valves/Actuators and Pressurization Systems
    - Maximum on-orbit lifetime of a cryogenic propulsion system is approximately 10 hours. Some lunar missions may require an in-space operational life of 4 to 12 months. Mars missions may require several years operation.
    - Chill-in of the MPS and Main Engine has occurred on the ground. Limited data on chill-in of the MPS/Engine in a 0-g on-orbit environment. Short duration data only.
    - Current SOA has been severely diminished by erosion in industry and government design capabilities
- **Possible Options**
  - Derivation of EELV & Shuttle MPS (scavenge STS MPS as available)
  - New MPS development, especially valves/actuators and to support CFM and in-situ propellant management
  - Cryogenic Fluid Management (CFM) Capabilities Needed
    - Advanced development of cryogenic propellant acquisition device (surface tension)
    - Advanced development of cryogenic storage capabilities
      - Low heat leak storage and feed system for multi-start, long duration missions is low TRL
    - Advanced development of cryogenic propellant management devices such as thermodynamic vent systems and cryo-coolers
      - Controls propellant residuals and supports zero boil-off

Opportunities for Technology Insertion
MPS

- **Safety and Reliability Improvements**
  - Long life, highly reliable / safe operation valves and actuators subject to wide temperature ranges
  - Integrated fault diagnostics and prognostics
- **Performance Enhancements / Enablers**
  - Light-weight, more efficient valves and actuators are needed to reduce/remove the need for on-board pneumatic systems and large solenoid valves.
  - The ability to support on-orbit refueling
  - Development needed for:
    - Deep throttle valves
    - CFM systems
    - In-Situ MPS systems
    - MPS components to support alternative propellants

Issues - Summary

- **General**
  - Detailed information on existing engine options or derivative options is not available to provide thorough assessment of ability to meet life, operations, reliability and cost targets. Analytical tools / models that adequately define the loads, environments and margins to ensure that life, operations, reliability and cost targets are met are lacking.
- **Reliability**
  - No clear solutions available to provide required improvements
- **Functional Characteristics (Isp, Thrust Level, T/W, etc)**
  - Several gaps exist with existing engine candidates.
  - Limited experience with alternative propellants.
  - No developed engine systems for key missions. No candidates in 90 klbf thrust class. J-2S 265 klbf engine requires redevelopment. For CEV TEI propulsion, no candidate cryogenic pressure or pump fed exists. There is no throttling cryogenic descent engine for the L/A.
  - Needed valves/actuators do not exist
  - CFM techniques and systems lacking
  - Integrated health management and crew safety systems lacking

Options for Improving Reliability on Existing Assets

- **Need for orders of magnitude reliability improvement from current SOA**
- **New design & development**
  - Design for robustness – design for requirements and design in redundancy where benefit clear
  - Physics-based reliability modeling
  - Verification tests at element, subsystem and system level to overstress conditions
- **Redesign**
  - Eliminate known design deficiencies
  - Incorporate improved design solutions where applicable
  - Increase design margins
- **Implement increased level of parts and process controls**
- **Perform a series of qualification tests to establish readiness of propulsion system and controlled processes and parts to support crewed flight**
- **Perform tests to verify physics-based reliability and the removal of failure modes**
- **Perform fleet leader testing?**

Issues - Propellants

- **Candidate Propellants (new engines, RCS)**
  - LOX/LH2 & GOX/GH2
    - Traditional, highest Isp, low toxicity risk, potentially common (propulsion, power)
    - For gases, storage systems evaluated for complexity, weight impacts
  - LOX/LCH4/CH4 & GOX/GCH4
    - Support volume efficiency and T/W, in-situ appropriate, higher Isp than hypergols, low toxicity risk
    - For gases, storage systems evaluated for complexity, weight impacts
  - LOX/GOX & Ethanol
    - Low toxicity risk, comparable Isp to Hypergols, higher TRL than CH4
  - NTO & MMH/Aerozene 50
    - Traditional, high toxicity
  - NTO/LOX & N2H4
    - Less toxic than NTO/MMH, increases Isp over NTO/MMH, power draw for heaters, higher TRL than CH4
  - Other - Tridyne, Gels, Monopropellants, Cold Gas
    - Improve performance and safety, impacts TBD

Summary and Conclusions

- Chemical Propulsion will play an enabling role in the new Vision for Exploration
- Existing propulsion systems and components can likely be utilized to satisfy some requirements
- Existing technologies can be incorporated into both existing and new systems to improve mission reliability, crew safety, lower cost, and system performance
- Key propulsion technology challenges remain